ChBE 411 - PBL 1*

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Abstract

A class project in which different energy storage options were analyzed for the Hyperloop Alpha.

1 CHBE 411 PBL 1 Project Report

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1.1 Introduction, Background and Motivation

On August 12 of this year, Elon Musk, CEO of Tesla Motors, unveiled his proposal for Hyperloop. This high-speed transportation alternative, he hopes, will be chosen over the approved railway to be built between San Francisco and Los Angeles. Musk believes "the underlying motive for a statewide mass transit system is a good one. It would be great to have an alternative to flying or driving, but obviously only if it is actually better than flying or driving" (Musk). This Hyperloop is proposed to cost only 10% of the budget allocated for the high speed railway and Musk also alleged that "the train in question would be both slower, more expensive to operate (if unsubsidized) and less safe by two orders of magnitude than flying" (Musk).

The Hyperloop is a method of near supersonic air travel that is supposed to be faster and cheaper than the current methods of transportation available. If built correctly, this method will not disrupt the residents of the cities the Hyperloop would pass through and would not require mass amounts of land in a straight line as the train would.

In the PDF where Musk revealed his idea, he detailed the basics of how the Hyperloop would need to be built, the amount of power needed to run it, the physics behind how the Hyperloop would run, and how its cars would be able to transport people and their vehicles. He has already optimized the path for the Hyperloop, calculated approximate costs, and analyzed the safety of this method of transportation.

This report contains evaluations of different energy storage options for the Hyperloop system and a decision regarding the most viable option for the Hyperloop passenger cars. It will address whether the

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storage system will be able to meet the criteria required for a functional Hyperloop, the most promising technology for this system, and the advantages and disadvantages of the most viable technology found for the Hyperloop.

The criteria for energy storage system are further detailed later in this paper. Lithium nickel manganese cobalt (NMC) ion battery, nickel-metal hydride batteries, and LightSail were the energy storage options analyzed for potential use on the Hyperloop passenger cars.

1.2 Lithium Nickel Manganese Cobalt (NMC) ion Battery:

In recent years, lithium-ion batteries have become an increasingly popular energy storage option because of their low cost, high specific energy, rechargeability, and lack of toxic material. They are currently used to store charge in many modern hybrid vehicles (Ballon, 2008). Though many different lithium-ion battery types exist, the Nickel Manganese Cobalt battery is of special interest. The Lithium NMC ion battery consists of a LiNiMnCo based cathode and a Graphite based anode, and is especially suited for applications where higher power is needed (AA Portable Power Corp). This battery has the optimized characteristics of the combination of Nickel and Manganese. Nickel has a high specific energy coupled with low stability, whereas Manganese forms spinel structures to obtain very low internal resistance, but also a low specific energy (Cadex, 2011). However, when they are combined it leads to a low internal resistance and specific energy as high as 0.155 kWh/kg - 0.19 kWh/kg (SAE International, 2011), which is up to four times higher than conventional lead-acid batteries (Corvus Energy). The team researched the specific industrial Lithium NMC ion battery, manufactured by Corvus energy, which has specific energy of 0.163 kWh-kg. Generally, Lithium NMC ion batteries have an efficiency of 80% to 90% (Valoen & Shoesmith). However, Corvus Energy battery exceeds this range and has a 99% efficiency rating (Perry & Simmonds).

The average cost of Lithium NMC ion battery is $0.4 /kWh (calculations taking into account battery cycle, installation, transportation, and battery costs can be found in the Appendix), which is comparable to market-value lead-acid batteries (AllCell, 2012). Most importantly, the Lithium NMC ion battery is considered particularly safe due to its Battery Management System (BMS), which manages voltage, current and temperature to ensure that battery is in safe working mode (Corvus Energy). Moreover, this BMS system monitors cells in the battery to maintain equilibrium of performance and reliability. Furthermore, it is possible to integrate safety alarms that can be programmed to shut down or isolate the system (Perry & Simmonds). NMC batteries have already been used as part of the hybrid drive in ferry systems and boats, helping to reduce CO2 emissions significantly (Perry & Simmonds). Since NMC batteries have proven successful in other large scale applications comparable to the Hyperloop's energy storage system, it should be considered for Hyperloop.

1.3 Nickel Metal Hydride (NiMH) Battery:

Nickel-metal hydride batteries are another common type of rechargeable battery. This battery is well-developed and is a more understood technology than lithium-ion batteries, which have been developed relatively recently. In comparison to Ni-Cd (Nickel-Cadmium) batteries, they have a considerably higher energy density and are much less toxic because they do not contain cadmium. Common applications for NiMH batteries include rechargeable electronic battery packs, satellite batteries, and early hybrid vehicle battery packs. The NiMH battery can typically retain optimal recharges for several hundred cycles, sometimes more depending on the method of recharge and discharge. (Kopera, 2004) Chemically, NiMH batteries store energy in the form of hydrides which in turn forms hydrogen when discharged. Metal hydrides compose the cathode, while a nickel oxide typically makes up the anode (Energizer Battery Manufacturing Inc., 2010). They have relatively high discharge rates nearing that of more recent lithium-ion batteries. Specific energy density for NiMH batteries ranges from .06-.12 kWh/kg, while specific power ranges from .2-1.0 kW/kg (Cadex, 2010). NiMH batteries have charging efficiencies of approximately 66%, less than that of the available lithium-ion options (Lund, 2013). NiMH batteries are also quite economical, costing only about $1.29 /kWh (See Equation 3b) in Appendix) (for the Hyperloop when taking into accounting for its usable

cycles in the calculations which can be found in the appendix). NiMH batteries tend to be relatively safe in standard applications. One potential safety issue is that hydrogen gas builds up within the cell as it is discharged. Typically this released hydrogen gas is vented freely; however this creates an explosion risk in non-ventilated areas, such as the tube for the Hyperloop. Many contemporary NiMH batteries have mitigated this risk through the inclusion of a pressure vent which can release excessive hydrogen. For the purposes of this analysis, the specifications of the GIGACELL, a specific NiMH battery pack, were used because the GIGACELL was designed to provide power to light rail trains. The specifications from this particular technology were taken and scaled up to match the Hyperloop requirements (Nishimura, 2013) (Kawasaki Heavy Industries Ltd., 2013).

1.4 LightSail:

LightSail is a new technology for energy storage which hopes to eliminate heat wasted due to the compression of air. This technology captures the heat energy created from the mechanical compression of air and then generates energy from the compressed air. This is achieved by injecting a spray of water mist during the compression of air. The mist absorbs the heat energy produced during the compression and stores it to be released when the compressed air is expanded again. Through their own experimentation, LightSail has found their product to have a 90% thermal efficiency for the entire process, have less than a 10 ºC increase in the temperature of air, and have their reciprocating piston compressor/expander running at 1,200 RPM, on a 100 kW scale, and offer over 500 hours of operation. Their power units are said to be 250 kW modules, offer 70% round-trip efficiency for its power sources and have a lifetime of at least 20 years. Their storage units are 1 MWH modules. They have had pre-sales of their technology with several investments made by the government. Despite pre-sales, this technology is not set to be on the market until next year (Lefkowitz).

1.5 Evaluation Criteria

In order to evaluate the technologies for the Hyperloop energy storage introduced above, seven criteria were considered: safety, physical weight, efficiency, durability/lifespan, cost, physical space, and renewability. Among them, safety was deemed to be the most important factor as the Hyperloop would be a large-scale public transportation system where a small safety problem could cause huge losses in both human lives and properties. A safe energy storage system is one that is unlikely to malfunction and does not cause serious consequences, such as large-scale property damages and life losses, even when it is not working properly. The second most important criteria are physical weight and efficiency. Physical weight of the energy storage system was of great importance because there would be strict constraints on the capsule's weight, as the capsule would need to be suspended above the tube surface. The technical document detailing the Hyperloop suggests that an energy storage system of 1,500 kg should be able to keep the 325 kW compressor motor running for 45 minutes (Musk). Therefore, the system must be below 1,500 kg while being able to provide 243.75 kWh of energy. Efficiency was another major criterion holding both economical and environmental implications. For instance, an energy storage system with a high specific energy but a low efficiency would be both expensive to charge and wasteful with much of the applied energy- both of these results would be undesirable. The durability of the energy storage system should also be considered because the Hyperloop would run continuously and rely on frequent recharges of the chosen energy storage system. Durability considerations included the average lifespan of a given energy storage option. An energy storage system with a long service life would reduce costs in the long run, while systems with a short service life would accrue higher costs overtime. The total cost of the energy storage system was also taken into account. Apart from durability and efficiency, which affect the operational costs, the initial cost of the energy storage system might also determine the practicality of an option given that many capsules would need to be built. The team also agreed that the physical space of the energy storage system should not be ignored. Since the capsule would have to fit into the tube and accommodate passengers and vehicles, the space for energy storage would be limited and thus this criterion needed to be considered. The last criterion for evaluating the energy storage system was renewability, which evaluated if the system could be used for a long term and

if certain components of the system might not be available relatively soon. This criterion was placed at the end because new technologies might emerge before the options become unavailable.

With these criteria in mind, the team evaluated the three energy storage options based on their performances on each criterion. The results of evaluations for the three energy storage options are listed in the following Pugh matrix. Ratings of the options were based on their performances relative to each other.

Criteria	Weighting (1-10)	Percentage Weight	Rounded Percentage	LightSail	Weight	NiMH	Weight	Li-ion	Weight
Safety	9	21.43	21	1	0.21	2	0.42	5	1.05
Physical Weight	8	19.05	18	2	0.36	1	0.18	4	0.72
Efficiency	8	19.05	18	4	0.72	2	0.36	5	0.9
Durability/Lifespan	7	16.67	15	5	0.75	0.5	0.075	1	0.15
Cost	6	14.28	13	5	0.65	2	0.26	4	0.52
Physical Space	3	7.14	10	1	0.1	3	0.3	5	0.5
Renewability	1	2.38	5	5	0.25	3	0.15	2	0.1
Final Scores				LightSail	3.04	NiMH	1.745	Li-ion	3.94

Table 1: Pugh Matrix comparing energy storage options.

1.6 Discussion

Assuming all the statements and values provided by Musk's pdf are valid, the aforementioned criteria were used to evaluate each of the energy storage options. An additional assumption included was that batteries used in the Hyperloop capsules would be removable, for quick capsule turnaround; the capsules would be able to dock at the station, have their batteries replaced, and quickly be available to transport the next group of passengers.

After weighing the criteria as previously described, the weights were converted to percentage values, and then these percentage values were rounded, so that the sum of the values totaled to 100. The team then proceeded to rank each battery type on a 1-5 point scale according to each criterion, by comparing it to the two other types, where 1 is low and 5 is high.

When rating each battery for safety, Lithium NMC ion received the highest rating due to its widespread use and built-in shutdown fuse that activates upon battery failure. NiMH batteries, used for electronics, were slightly less safe, with the risk of hydrogen release when overcharged. In a normal setting, these risks are minimal, but since Hyperloop deals with low pressure settings, any gas release, especially that of flammable gases, was a safety concern. LightSail was ranked last, due to its lack of testing and risk of massive failure in the event of a pressure leak.

Next, the physical weight rankings were based on how close the battery weight was to the recommended 1,500 kg, with lighter batteries getting better ratings. When calculated, the weight of Lithium NMC ion batteries to be approximately 1,500 kg—the only battery to be within the recommended weight range. The next lowest weight requirement was LightSail, requiring about 4,535 kg to produce the proper power (See Equation 5 in Appendix). NiMH was the heaviest option, requiring 11,800 kg of GIGACELL batteries (See Equation 3 a) in Appendix). This exceeded the recommended weight by an order of magnitude, and

is an altogether unrealistic choice for energy storage based on weight. This also far exceeded the weight recommendation.

For battery efficiency, the main consideration was how well the battery expends its stored energy. The Lithium NMC ion battery by Corvus Energy, with an efficiency of 99%, was a clear winner in this category. LightSail, with a thermal efficiency of 90% and roundtrip efficiency of 70%, was ranked second. NiMH batteries, on the other hand, are notorious for rapid rates of self-discharge, with a markedly lower efficiency of 66%. NiMH batteries ranked last in the category of efficiency.

The next consideration was battery durability and lifespan, looking at the number of cycles each battery can be charged and discharged until it must be replaced, with a slight modification for LightSail. The research into a specific brand and model of Lithium NMC ion batteries yielded a lifespan of over 3,000 cycles. For NiMH, this value is an order of magnitude less, at 200-300 cycles, while LightSail has an estimated lifespan of 20 years (Lefkowitz). After converting each cycle value to a time value, the Lithium NMC ion was projected to last just under 1 year and NiMH to last about 1 month (See Equation 1 in Appendix). Thus the batteries were ranked in decreasing order, for durability and lifespan: LightSail, Lithium NMC ion, and NiMH.

For battery cost, each battery's cost per kWh was compared. The costs were calculated by averaging the initial cost of the battery into the entire battery life, plus the price of electricity for recharging the battery. Our calculations yielded a lowest cost for LightSail with a cost of about $0.207/kWh (See Equation 5 c) in Appendix), assuming that it would be effective for 20 years. Second was Lithium NMC, at about $0.4/kWh. NiMH, costing $1.292/kWh (See Equation 3 b) in Appendix), is the most expensive of the three due to its short lifespan. Thus, our final rankings were, in decreasing order, Lithium NMC, LightSail, and NiMH.

Another important factor is the physical space needed for the battery, using number of cells and volume/cell to calculate the volume required for each battery type. Lithium NMC ion was ranked first, taking up only about 760 L (See Equation 3d) in Appendix). NiMH batteries, on the other hand, were calculated to take up a volume of about 4,683 L (See Equation 3 a) in Appendix). Lastly, LightSail was calculated to have a value drastically higher than either of these batteries, at about 18,689 L (See Equation 4 a) in Appendix), and thus was given the lowest ranking.

Lastly, the renewability of the batteries and the resources inputted to the battery's production were addressed. Although hypothetical analysis of each battery's physical capabilities does not necessitate addressing the long-term environmental impact of a battery choice, realistically implementing a chosen battery type would require an analysis of this criterion. In terms of resource use, LightSail was a clear choice to be ranked first, as it uses air and water, resources that are relatively abundant on earth. NiMH batteries were ranked next, as they require mined nickel, which is nontoxic, and does not contain Cadmium, meaning that improper disposal of NiMH batteries would cause less pollution than other versions of nickel batteries. In addition, the nickel in these batteries may be recycled. Of the three batteries, Lithium NMC ion battery ranked last as it consists of the most limited resources in comparison to the other batteries: lithium, nickel, manganese and cobalt, of which nickel is the only recyclable metal.

After ranking each of these criteria and weighting these rankings with the percentages discussed in the previous section, these values were summed up to obtain numbers that reflect the overall utility of each option, as applied to the Hyperloop and with the assumptions stated at the start of this section. The final results are shown in Figure 1 above. Lithium ion battery, specifically NMC battery, received the highest score of 3.94 and was deemed the most viable option for the Hyperloop's energy storage system for its safety, high efficiency, and reasonable weight and volume. LightSail was ranked the second with a score of 3.04, being extremely large and untested; it might not be suitable for the Hyperloop as for now. NiMH battery was ranked the last mostly due to its physical weight, low efficiency, and short lifespan with a score of 1.745.

1.7 Pitfalls, Limitations and Alternatives

Most great things in life do not come without flaws, and these technologies are no exception. Even the recommended technology, Lithium NMC ion battery, could be potentially too heavy for the Hyperloop capsules. Although the theoretical weight of NMC needed to power the compressor is calculated to be 1,495 kg (See Equation 2 c) in Appendix), falling right below 1,500 kg as proposed in Musk's technical proposal,

this weight does not include any accessories of the battery, such as the above-mentioned BMS for safety control. Therefore, it is possible that heavier NMC batteries might be needed to power the Hyperloop's compressor, which might pose limitations on the functioning of the capsule. In addition, it also has some limitations of renewability and durability as compared to LightSail. Since this battery consists of four metals, their renewability is a consideration. Although none of these metals are scarce, yet relative to LightSail and NiMH, they are not as available, which could become a problem in the future. Moreover, Nickel is the only metal among the four that gets recycled. The specific Corvus NMC battery has 3,000 cycles but the LightSail can be used for more than twenty years. Another limiting factor is the blending process of Nickel, Manganese and Cobalt, if done inadequately it can lead to different metallic interactions which will affect the battery performance (Pistilli). Moreover, even a small intrusion of a metallic dust particle can have serious consequences on the battery's chemistry. Another limitation of Lithium NMC ion batteries is that they can only be tailored to either high specific power or high specific energy (Cadex, 2011). In the case of the Hyperloop, it is the specific power that is more important as it needs to hit a certain power threshold to run. Regarding specific energy, however, the battery only requires a minimum energy capacity in order to last the trip.

While LightSail has the potential to be a viable means of energy storage for many processes in the future, it is presently severely limited by the sheer amount of volume necessary to store energy. At the pressure of 3,000 psi (Brown) LightSail requires a volume of 18,689 L (See Equation 4 a) in Appendix) to support the 325 kW of energy needed for one trip on the Hyperloop making the size a much larger than the other options. Additionally, LightSail's weight requirements are greater than the 1,500 kg allocated for energy storage. Making the assumptions that air at 204.14 atm (3,000 psi) is an ideal gas and that the containers are filled only with air and the weight of water is negligible, 4,535 kg of air are needed to store 325 kW (See Equation 4 b) in Appendix). This 4,535 kg only accounts for the weight of the air and does not take into account the weight of the containers which will store the air. On the issue of safety, while LightSail states that their design is safe, the pressure difference between the compressed air at 204.14 atm and the surroundings is cause for pause. A pressure leak could be disastrous and would not be an easy fix without proper fail-safe technology. As an alternative, however, LightSail could be a better energy storage option for the linear motors along the Hyperloop as this option would allow the large air tanks to be stored outside the tube. (See Equation 5 in Appendix for detailed calculations for LightSail).

NiMH batteries have been proven a viable option for energy storage in several applications similar to the Hyperloop, (namely light rails and hybrid cars). Despite their broad production and low cost, they really aren't practical as an energy storage method for Hyperloop due to their limited lifespan, and large weight and volume requirements**.** Chemically, NiMH batteries are pretty finicky and require specific charging and discharging rates to retain effectiveness. They work best with a shallow discharge and lose efficiency after a couple hundred discharge cycles. It is possible that charging and discharging of the batteries could be optimized for the Hyperloop, allowing a much increased lifespan that would be acceptable for longer-term use.

Unfortunately, solving this problem still doesn't alleviate the issue of the quantity of NiMH cells needed to power a capsule. Due to lower specific energies and power densities, the Hyperloop passenger capsule would require almost over 11,000 kg of NiMH batteries for its 35 minute journey (See Equation 3a) in Appendix). The 11,000 kg would also require approximately 4,500 L of precious cargo space (See Equation 3a) in Appendix). These obstacles could be a result of the specific industrial battery that were chosen to scale up to Hyperloop requirements. The GIGACELL battery pack is specifically designed for light rail applications. Light rails have a considerably shorter reach and energy requirement in comparison to the Hyperloop. This just means that the Hyperloop capsule requires many more batteries. Perhaps a NiMH battery designed with the Hyperloop in mind could provide similar outputs with reduced weight and volume. Even if weight and volume were reduced some, they can't be completely reconciled due to constraints imposed by NiMH batteries' energy and power densities.

NiMH batteries present a unique safety concern in the context of the Hyperloop capsules. Normally the cells are relatively safe. As mentioned before, most modern NiMH batteries contain a pressure vent which releases excess hydrogen buildup. When used in cars or the light rail this hydrogen release can vent into open

air. If used in the Hyperloop however this potentially explosive hydrogen would need to be stored onboard the capsule. This issue could be resolved by storing the hydrogen in static-free and/or oxygen-free areas of the capsule. Even still, it is a complication that would need to be addressed.

1.8 Conclusion

The critical design component of Hyperloop is the suspension the capsule within the tube along its path. For achieving this goal, Musk proposed to install an air compressor fan at the node the capsule, which would divert the air to the rear of the capsule. In doing so, capsules would not touch the wall of the tube while they are travelling along the tube, which, Musk estimated, would greatly decreases the frictional force the capsules experience at near supersonic speed. The major problem associated with the compressor fan is to find the suitable energy storage system that can supply enough energy to continuously power the compressors. Musk himself mentioned the Lithium ion NMC battery and LightSail system as two possible systems that can possibly be used in the Hyperloop. In addition to the two options above, one additional energy source, Nickel Metal Hydride battery, was considered in this report as well..

The main criteria to evaluate three different energy systems are safety, efficiency, cost, durability, weight etc., and different weighting is given to each evaluation criterion for thorough analysis. In the comparison discussed above, the safety, physical weight, and efficiency are considered most importantly. In the Pugh Matrix, the Lithium ion NMC battery is evaluated as the most viable energy storage systems. Lithium NMC ion battery has been widely used in industries and everyday life due to its superior safety and efficiency. The Lithium ion NMC battery also has the greatest advantage as a result of its outstanding performance on safety, the most important consideration in designing the mass transportation system. The safety of LightSail is still doubtable because it is not fully commercialized yet. Nickel metal hydride and Lithium ion NMC batteries both contain potential chemical hazards, though Lithium ion NMC is known to be less dangerous within the context of this application. At the same time, the Lithium ion NMC battery is chosen as the viable option because it will take the smallest volume and weight to meet energy and power requirements proposed by Musk. As a result, the Lithium ion NMC battery is recommended as the most plausible energy storage system for the Hyperloop out of three candidates. On the other hand, LightSail, if fully commercialized in the near future and being able to function properly as described by the company, should be considered again since the technology shows its advantages over other energy storage systems on its renewability, lifespan and cost.

Appendix

Please find the appendix as the attached pdf file.

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